Articulating five liquids: A single speaker ultrasound study of Malayalam

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Abstract

We investigate the lingual shapes of the five liquid phonemes of Malayalam: two rhotics, two laterals and a more problematic 5th liquid. Ultrasound is used to image the mid-sagittal tongue surface, mainly in an intervocalic within-word /a__a/ context. The dark retroflex lateral and trill have a retracted tongue root and lowered tongue dorsum, while the three other clear liquids show advanced tongue root and dorsal raising. The 5th liquid is post-alveolar and laminal. Some additional data from an /a__i/ context is considered: the liquids are slightly clearer before /i/: all have a slightly advanced tongue root, and all bar the trill show palatalization. Dynamically, the trill and retroflex lateral have a very stable tongue root in /a__a/, and the 5th liquid has unusual anterior kinematic properties which require further investigation.

1. Introduction

1.1 Background

As part of its liquid inventory, Malayalam (a Dravidian Language of southern India, Krishnamurti 2003) has two rhotics (/r/ and /ɾ/, a trill and a tap), two laterals (/l/ and /ɭ/, an alveolar and a retroflex lateral respectively) and a 5th liquid, most commonly labelled /ɻ/. This last segment has been analysed either as a rhotic, specifically a 'voiced sublamino palatal approximant' (Asher & Kumari 1997:419) or as a lateral, specifically a 'voiced retroflex palatal fricativised lateral' (Kumari 1972:27-28). The only two experimental studies on this general topic prior to 2010 were on the related language Tamil, and in these the 5th liquid was classed as a central retroflex approximant (McDonough & Johnson 1997; Narayanan et al. 1999), but more recently, Punnoose (2011) and Punnoose et al. (2012) have explored the Malayalam liquids from both phonological and phonetic points of view (as well as comprehensively reviewing the existing literature), revealing greater complexity. These recent papers draw attention to the importance of secondary resonances in the system of oppositions as well as contrasts based on primary manner and place of articulation.

In addition, some contemporaneous research on Kannada is using ultrasound to explore retroflex stops in relation to other lingual obstruents (Kochetov et al. to appear; Kochetov et al. 2012), which will provide results that will dovetail to some extent with those presented here.

While it might be possible to definitively classify the 5th liquid either as a rhotic, a lateral or a non-rhotic central approximant, a non-deterministic or 'fuzzy' approach to phonological systems (cf. Scobbie & Stuart-Smith 2008) assumes there may be underlying phonological and phonetic reasons for its ambiguous status. The phonological patterning of /ɻ/, for example, offers a somewhat mixed picture regarding its lateral/rhotic identity, and the phonetic characteristics relevant to distinguishing it from the other liquids might likewise be variable or gradient. On the one hand, the rhotics and the 5th liquid are the only consonants not to have a singleton-geminate contrast. On the other hand, /ɻ/ and /ɭ/ tend to alternate in certain morpho-syntactic contexts. For more detail on these complex patterns, see Punnoose (2011).

Punnoose (2011) and Punnoose et al. (2012) have shed new light on the sound system using production data from eight adult males. These detailed studies constitute the first acoustic investigation of Malayalam /ɻ/. One of their aims was to consider the hypothesis that /ɻ/ is a third rhotic. Also, in (mainly auditory) impressionistic terms, they have found that /ɻ/ sounds like a clear post-alveolar central approximant, and that it appears to lack retroflexion, in the sense in that it lacks strong retraction with perhaps sublaminal contact during a forward-moving constriction.

In addition, they have explored the acoustic phonetic nature of the liquid system, exploring a number of parameters that can distinguish (or not) these segments from each other. Acoustically, however, it is hard to definitively categorise /ɻ/ as either rhotic or lateral. Its first two formants (especially F2) were found to be close to the values for one rhotic (the tap) and one lateral (the alveolar approximant), namely /ɾ/ and /l/, which Punnoose and colleagues classify as having a *clear* resonance, while its F3 and F4 pattern closer to the values for /r/ and /ɭ/, which they class as having a *dark* resonance.

1.2 Summary of methodological and descriptive goals

The rhotic system of Malayalam has a binary phonological opposition, which is traditionally characterized as tap vs. trill. A secondary phonetic correlate of this contrast is a clear vs. dark resonance difference (for the tap vs. trill respectively), which is the *same* secondary resonance distinction found in the alveolar and retroflex laterals (respectively). It would therefore be useful to get information on the secondary and primary articulation of both rhotics, both laterals, and the 5th liquid. No single articulatory technique can provide all the information required, but ideally we would use one which is:

a) Fast enough to be able to image the tongue cleanly during the short constriction phase, and therefore able to produce a single lingual shape to characterize both approximant and more ballistic manners of articulation;
b) Frequent enough to be able to reveal aspects of the fast changes in tongue shape and location for coarticulatory and ballistic motions before, during and after the liquid;
c) Capable of revealing aspects of tongue root articulation relevant to secondary articulation as well as aspects of the blade and tip kinematics relevant for the primary place and manner of articulation.

Here we use high-speed Ultrasound Tongue Imaging (hs-UTI). Ultrasound scanning provides us with a mid-sagittal, two dimensional view of the tongue (Davidson 2012). Ultrasound is a convenient non-invasive technique, but it should be noted that in order to stabilize the probe to the head, protocols need to be adopted which shorten data collection time due to speaker fatigue, and also that *high-speed* UTI requires more expensive and specialized instrumentation than normal video-based UTI. The low cost and portability of the latter make it more likely to be used in fieldwork (Gick 2002, Lawson et al. 2008, Lawson et al. 2011), but its longer data-capture window is more subject to spatiotemporal artefacts (Wrench & Scobbie 2006) and thus is harder to synchronize to the acoustic signal. For many purposes, the approximately 60 frames per second that is possible with de-interlaced video UTI should prove sufficient, but to capture details of very fast moving ballistic flaps or clicks, for example, hs-UTI is likely to be preferable (Wrench & Scobbie 2011). The non-dynamic findings presented here would be easily observed using video UTI.

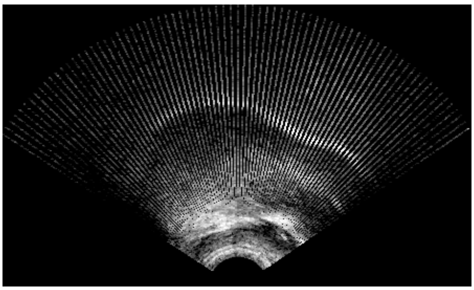
We will look for articulatory correlates of the clear vs. dark distinction by examining the position of the tongue root and dorsum. The relative location of anterior parts of the tongue, whether blade or tip, will be examined to reveal differences in constriction location and shape, which can be related to the primary place and method of articulation. These comparisons will be largely qualitative and tentative, since this is a single-speaker study, and one which uses a very small dataset. Our interpretative comments are based on highly accurate instrumental data, the nature of which we will try to convey in illustrative figures below, guided by what we have found from our earlier acoustic and transcriptional phonetic research.

2. Method

2.1 Instrumentation

Each digital ultrasound image was created from a single scan from a probe held by a stabilizing headset (Articulate Instruments 2008, Scobbie et al. 2008). The scan rate / frame rate is flexible, up to around 400 frames per second (fps), and was set at 100 fps (one frame each 10 ms), synchronized to the audio via the high-speed Articulate Assistant Advanced™ system (Articulate Instruments 2011, Wrench & Scobbie 2011), based around an Ultrasonix SonixRP scanner remotely controlled via Ethernet from a PC. The transducer was a short-handled paediatric microconvex probe operating at 6 MHz. The field of view was set at 112.5°.

Acoustic data was recorded on the Articulate Instruments multichannel acquisition system at 22,050 Hz. In this system, a hardware pulse generated at the moment that each ultrasound scan is made enables accurate synchronisation with the acoustics. Each ultrasound frame is then stored by the AAA system as a set of raw echo-pulse return data (Figure 1a) from which a standard two dimensional image is created when viewed (Figure 1b). A semi-automatic line-fitting process within AAA was used to trace the location of the tongue surface. Figure 1a shows how an ultrasound scan samples the space in the field of view: pulses spread out the further they get from the probe. Each image is therefore less accurate in circumferential as opposed to radial dimensions. This may be by as much as around an order of magnitude (e.g. ~3 mm as opposed to ~0.3 mm). When the tongue surface is orthogonal to the echo-pulse beams, distance from probe data can be very accurate, but a tongue surface that is retroflexed or otherwise positioned so that it is approximately parallel to the beams is picked up less accurately, due partly to greater scattering of the ultrasonic echo, and partly as an artefact of image processing: the tongue surface will be detected at the location of each echo-pulse beam, discretising its location in little steps, as we will see below. A potential imaging problem is that strong retroflexion, where the tongue tip curls back during a sublaminal contact, may not be visible. Such articulations will look similar to highly apical supralaminal post-alveolar or palatal articulations in static images. Therefore, what appear below to be very retracted apicals are classified by us as retroflex. We may however be underestimating the extent of this retroflexion by not being able to detect any sublaminal contact. A paired UTI/MRI (or UTI/EMA) dataset would be useful to help investigate this issue further.

a. 

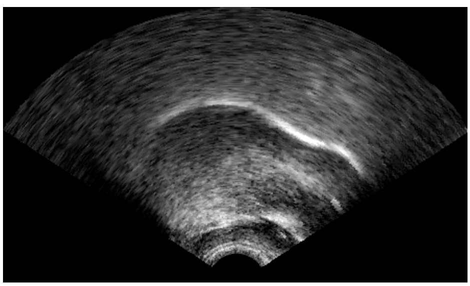
b. 

Figure 1 – Ultrasound images of a single frame. Anterior is to right. a. The raw data return shows echo data from 76 echo-pulse scan-lines radiating from the probe (the curved indent, bottom centre). They are each 8 cm long. Bright areas result from a higher intensity of echo, which is particularly strong on the tongue-air boundary. b. This standard 2D image is constructed from this echo pulse data by AAA software, interpolated in arcs to fill in gaps between scan-lines.

For analysis, we used the AAA software. We superimposed a measurement fan of 42 radial measurement lines onto images such as the one in Figure 1b (the 42 radii being independent of the number of scan lines or the size of the field of view). A single control point (or "tag") on each fanline radius was used to tie an analysis curve to the location of bright tongue-air boundary, if this indication of the tongue surface is indeed visible at all in that area of the measurement fan. Gradient confidence measures of this edge-tracking were available when automatic edge-tracking fitting was used. Hand-corrections were used as an override if needed. Thus a tongue curve was created for each frame of interest with at most 42 coordinates. We chose the AAA option to smooth each curve slightly to avoid tracking noisy aspects of the image too closely.

In this study, each word spoken (for materials, see below) provided a single representative tongue curve for one target liquid. These averaged in AAA to provide a mean curve, a process which also provides the standard deviation of the location of the contributory tag points along each fanline.

2.2 Speaker and protocol

The male adult speaker and the second author are both (multilingual) native speakers of the Central Travancore dialect of Malayalam. The second author explained the materials and the orthographic conventions for the Latin script presentation (Table 1) orally and using Malayalam orthography. The speaker was familiar with these conventions. Latin script had to be used for software reasons. She also monitored data collection to make sure there were no mistakes, intervening when needed to elicit a correction. The speaker also corrected himself on a few occasions, and showed a high level of awareness of his target productions. Words were recorded in pairs for speed of data collection – an audible beep accompanied the appearance of the prompt on screen, and the speaker then said the word twice with a small pause in between each token. The speaker's bite plane was also imaged to enable rotation of images to the occlusal plane, and images of swallowing were captured to provide an indication of the location of the alveolar ridge and hard palate.

2.3 Materials

TAP	TRILL	ALVEOLAR	RETROFLEX	5TH
/ɾ/	/r/	/l/	/ɭ/	/ɻ/
ara 4	**aRa 8**	**ala 4**	**aLa 4**	**azha 4**
		mala 4		**mazha 8**
maram 8		**malam 4**		
				pazham 8
ari 8	**aRi 4**	**ali 4**	**aLi 4**	**azhi 4**
ira 8		**ila 8**		**izha 8**
kara	*kaRa*	*kala*	*kaLa*	*kazha*
kari	*kaRi*	*kali*	*kaLi*	*kazhi*
mura		*mula*	*muLa*	
pura				*puzha*
			poLa	

Table 1 – Materials, a mix of real words and pseudo-words (underlined), with a count of the number of tokens elicited (and analysed). Italicised words are not analysed here.

The materials were designed to elicit minimal sets of all five liquids, which is possible only in intervocalic position, with multiple repetitions, within 20 minutes to avoid speaker discomfort, and in mainly low vowel and non-lingual consonantal contexts to reduce coarticulation effects. The liquids were mainly elicited between /a/ vowels, or in an /a__i/ context, with a few other tokens in other contexts to provide further detail. Pseudo-words were kept to a minimum, and filled out the /a__i/ frame. For methodological simplicity labial consonants (or none) in the carrier words were preferred, to avoid unwanted lingual coarticulation. No carrier phrase was used, again to minimize coarticulation and to speed up data collection. In addition, a passage was elicited (presented in Malayalam orthography). This has not yet been analysed.

At least four tokens of each (pseudo) word were captured, with 8 tokens for some. The number of tokens elicited for words formally analysed in this paper is also given in Table 1 (in bold typeface). We will focus here on the core /a__a/ context (with no other consonant or a labial consonant) which provides most tokens, though, looking ahead, it is clear that words with /k/ or with other vowels show similar behaviour.

2.4 Annotation and data extraction

Figure 2 attempts to convey, in a single composite image, the way a tongue surface changes shape and location in time in the mid-sagittal plane, by presenting an overlay of a temporal sequence of tongue curves, using /ɾ/ as an example. Each of these curves has been semi-automatically traced over an image like the one in Figure 1b using AAA software. During the actual annotation process, however, a time sequence of un-traced raw images was examined one at a time in a moving sequence, manually-controlled, from which one frame was chosen on a holistic basis as being the one containing a tongue shape best characterizing the target. Thus normally from each word only one tongue curve was drawn, on the target frame. It was then extracted and averaged together with shapes from other tokens of the same target. Plotting the *average* target enables an accurate comparison of the position and shape of each of the five liquids.

The basis for selecting a single frame from the ultrasound sequence was as follows. The frame chosen (by the first author) was the one which seemed to characterise the consonantal constrictions as a whole, but with primacy given to the anterior articulation. For /ɭ/ and /ɻ/ the frame chosen was the one with the most strongly retracted and raised blade, often achieved for just a single frame or two, while the other three liquids were captured at a frame of a stable (alveolar) constriction. For the rhotics and /l/, if many frames seemed equally characteristic of the anterior articulation, the most extreme root articulation dictated the choice of frame.

Figure 2 also shows the overall orientation of the tongue shape. It has been rotated so that the speaker's occlusal place is horizontal (at 48 mm high). The location of the hard palate can be estimated by examining the images of swallowing, because the tongue presses up against the hard palate during the swallowing action. A palate shape can be superimposed on plots of the lingual targets in the AAA workspace (see Figure 4 below). The target shape for the /ɾ/ in Figure 2 corresponds to the last in the sequence plotted (i.e. with the highest blade). It was the curve used as the basis for calculating the mean tongue configuration for /ɾ/. The /a/ curve, however, is for illustration – in this token it was early in the vowel, but no particular convention was used to identify it. Overall, Figure 2 conveys something of the nature of tongue movement and how segmental targets can be identified; in this case an intervocalic liquid.

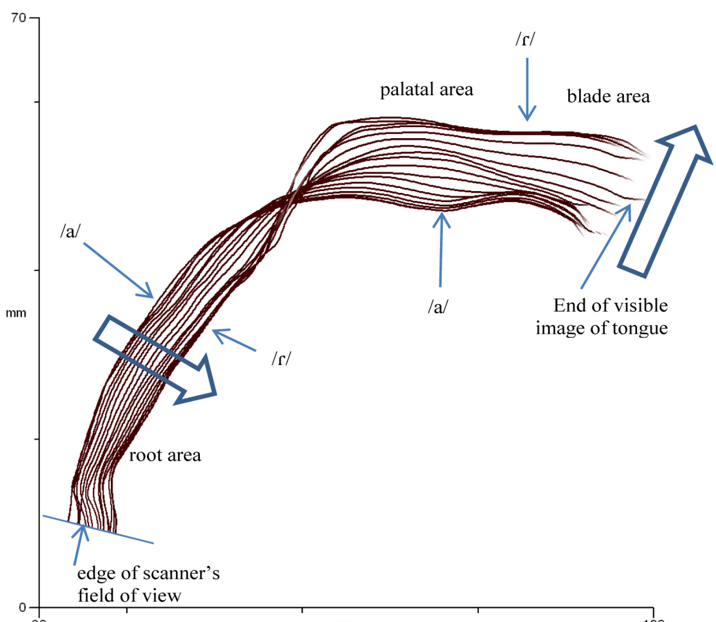


Figure 2 – Example of the dynamic movement from /a/ into the tap /ɾ/, rotated so that the occlusal plane is horizontal. Curves are 10 ms apart in time, and this example lasts 160 ms. The direction of movement in time is shown by the large arrows. The origin of the measurement space is arbitrary – the lower edge of the upper teeth are approximately at (110, 50). Tick marks are at 20 mm intervals. The same axes are used in all figures, to enable comparison of pharyngealisation and palatalization.

Figure 2 is not merely illustrative, however – it is also a useful way of conveying the dynamic and coarticulatory aspects of the articulation of an intervocalic liquid, as we will see below.

Note that as the tongue tip raises, an air pocket may appear under the tip. This sub-lingual cavity is particularly important as a resonant chamber, influencing the acoustic properties of the liquid sounds – but unfortunately air (and hence the sublingual cavity) is impenetrable to ultrasound at the frequencies used in scanners. A raised tip is likely to be invisible to ultrasound: the corollary is that neither the anterior termination of the tongue surface in an ultrasound tongue image nor the right-hand end of the curve traced from it will necessarily correspond to the tongue tip itself, just to the most anterior part of the blade which is imageable. Moreover, when the tongue is in contact with the hard palate or alveolar ridge, the discernibility of the surface often diminishes.

Finally, by measuring the distance between the curves in Figure 2 it is possible to estimate the speed of the tongue blade surface as it moves through the oral cavity. Just a single typical token of each liquid was quantified, as an indicative measure. We measured the speed of the blade orthogonal to the direction of travel – thus most segments were examined moving along a trajectory that was roughly vertical in these figures, whereas the forward movement of the retroflex flap was captured in the analysis of its motion (see Figure 9). From these tokens, a rough articulatory duration of 'time at the target' was also calculated, based on the number of frames where the tongue blade was moving slower than a threshold of 30 mm/s.

3. Impressionistic results

The impressionistic phonetic realisations of our single speaker's rhotics and laterals was broadly comparable to those in Punnoose (2011) and Punnoose et al. (2012). Primary place and manner were as expected, with the following exceptions: the tap /ɾ/ was sometimes quite stop-like and sometimes fricated; the trill /r/ was often undershot, as seems typical for phonemic trills (Jones submitted); the lateral /l/ was sometimes fricated.

In terms of secondary resonance, the /ɾ/ and the /l/ both sounded relatively clear while the /r/ and the /ɭ/ were both impressionistically darker in resonance, as Punnoose and colleagues have found. The 5th liquid /ʐ/ sounded post-alveolar, neither strongly clear nor dark, it was often fricated, and had some mild rhotic qualities in the approach to maximum constriction (cf. the temporally asymmetrical frication and formant movements in Figure 3).

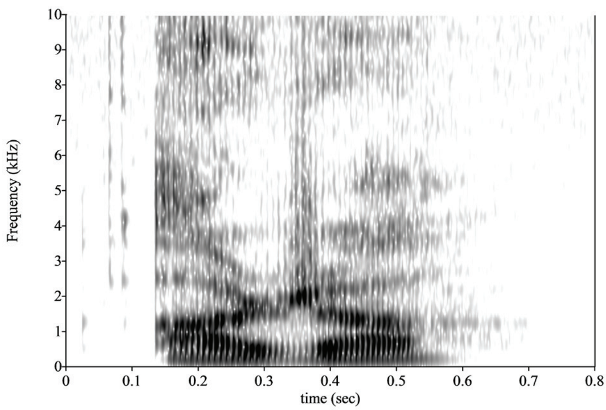


Figure 3 – Example token of azha /aʐa/ showing temporal asymmetry in its formant movement and frication.

When the liquids were before /i/, mostly there were only small differences between /aCa/ and /aCi/: /ali/ was more consistently fricated than /ala/, but the number of tokens is too small to draw conclusions from. Bigger auditory differences from /aCa/ were observable for liquids following /i/, for the small dataset available. Only the clear liquids appear in this context, and all were fricated.

In /aɾi/, as with /aɾa/, the tap often was stop-like, but in /iɾa/, it was more like a short fricative or a fricated tap. The alveolar /l/ in /ila/ was strongly fricated, probably due to the high tongue position. The /i/ in /iʐa/ sounded less peripherally high and front that the /i/ in /iɾa/ and /ila/, and there were formant differences.

4. Articulatory results

4.1 Single frames

Overall, a different spatial tongue shape was found for each liquid (Figure 4), in addition to dynamic differences which will be explored more below.

Bearing in mind that the tip might not have been imaged, in Figure 4 we can see a slightly tighter constriction between what is probably the alveolar region and the tip/blade for /l/ than for the other liquids – the blade is pretty parallel to the occlusal plane, and lies about 12 mm above it. The comparable part of the tongue in both rhotics appears to lie about 3 mm lower. In the tap, as with

/l/, the blade is pretty flat (then raises slightly in the dorsal area), whereas for the trill, the blade slopes ‘downwards’, about 6 mm closer to the probe. Strong retroflexion is clear in /ɭ/, causing some artefacts that result in the surface appearing to pass through the hard palate[1]. The 5th liquid /ʐ/ is clearly post-alveolar and laminal.
Clear pharyngealisation can be seen in the dark /ɭ/ and /r/, with root retraction of about 1 cm compared to the three other liquids. Slight raising of the front of the tongue, which may be a type of weak palatalization, can be seen in the clear /ɾ/ and especially /l/, and also in the 5th liquid /ʐ/ in addition to is post-alveolar close constriction. The 5th liquid looks quite like a bunched tip down rhotic (Lawson et al. 2011).

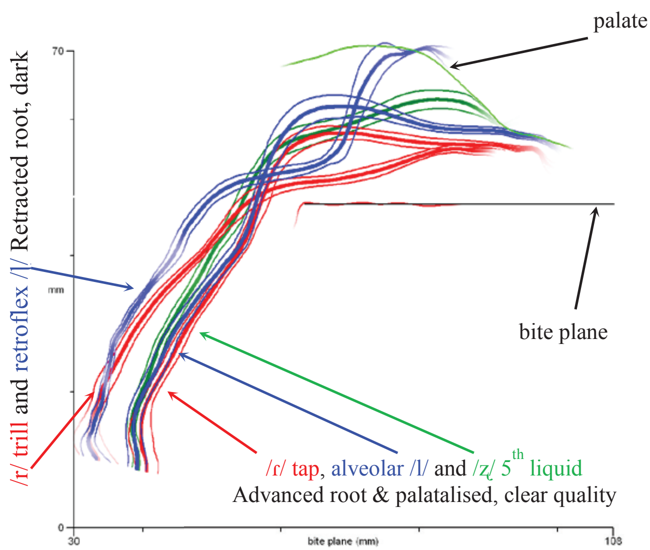


Figure 4 – Averaged tongue shapes for the five liquids between /a/ vowels. Thick line indicates the mean, flanked by ±1 s.d. The rhotics are in red, laterals in blue, 5th liquid in green.

Similar locations and shapes can be seen for the liquids in the contexts of the other vowels examined, with some slight coarticulatory differences.

[1] Recall that the retroflex lateral may in fact have a sublaminal contact, but since we are unable to detect the ‘looping back’ in static images, we have to ‘join the dots’ to give the impression of a supra-laminal contact.

4.2 Dynamic analysis

A dynamic qualitative articulatory analysis was undertaken, and the results will be conveyed using typical single tokens below. A tongue curve was traced onto every frame from a stable vowel position before the liquid to one after it. The tongue roots are generally dynamically active, except in /aɭa/, in which only the blade moved, as part of the rapid forward moving flap. Overall, the rhotics (/r/, /ɾ/) and laterals (/l/, /ɭ/) had relatively simple motion paths which are well-represented in the figures, but the 5th liquid /ʐ/ had a more complex blade motion, which we have tried to represent with a bendy arrow.
In each of the figures below, representing a single token, the left panel represents the movement from the preceding vowel to the target, and the right panel from the target through to the following vowel.

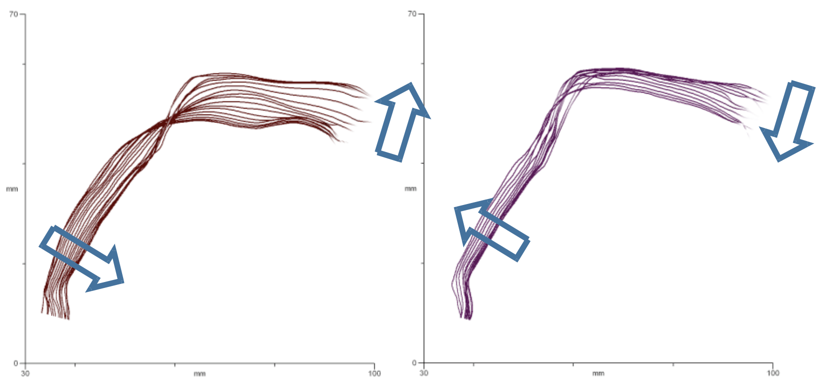


Figure 5 – Example of the dynamic movement into and out of the clear tap /ɾ/ in an /a/ context. The left frame shows the closing gesture from /a/ into the target frame for /ɾ/, and the right frame the opening gesture from /ɾ/ into /a/. Curves are 10 ms apart in time, and the arrow shows the direction of movement in time. These conventions apply to the other dynamic figures below.

The slightly wider spacing of the traces in the left panel of Figure 5 near the tip, in the start of the tap, show the most rapid movement in the whole sequence, as the blade and tip move rapidly upwards. The tongue does, however, stay in the constriction location for a couple of frames – the shortest constriction is around 20 ms.

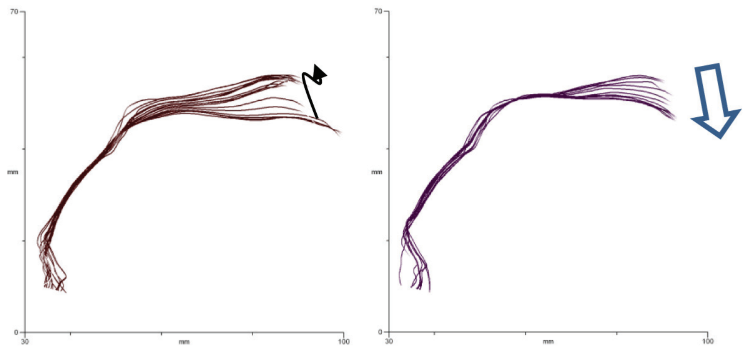


Figure 6 – A single token of the dynamic movement into and out of the dark trill /r/. The left panel includes more than one raising-lowering cycle of the blade (and tip), indicated by the thin arrow.

One of the most striking things about the trill is the stability of the root in the /a__a/ context. In the left panel, it is perhaps not obvious that there are two trill events in this /r/, as the tip raises quickly to the maximum height (shown by the widely spaced curves), lowers by a few millimetres, and raises again. The time spent in this location for one constriction of the trill is short, around 30 ms. The up-and-down motion of the blade can be easily seen in a velocity trace (Figure 7). We can see rapid upwards movement of around 250 mm/s at 50 ms, followed by a downward-upward-downward-upward trilling motion between 75 ms-140 ms approximately, followed by downwards movement towards the next vowel from 150 ms.

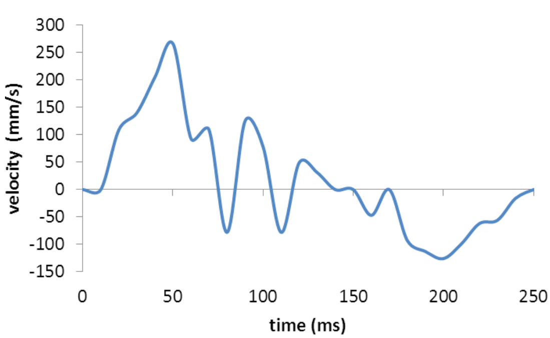


Figure 7 – Velocity upwards (positive values) and downwards (negative values) of the blade in trilled /ara/.

The alveolar lateral (Figure 8) is clearly palatalized, with a consistent speed of transition. The time spent at the constriction is around 70 ms, around twice as long as the other liquids. The rather 'pointy' palatalization may be an imaging artefact.

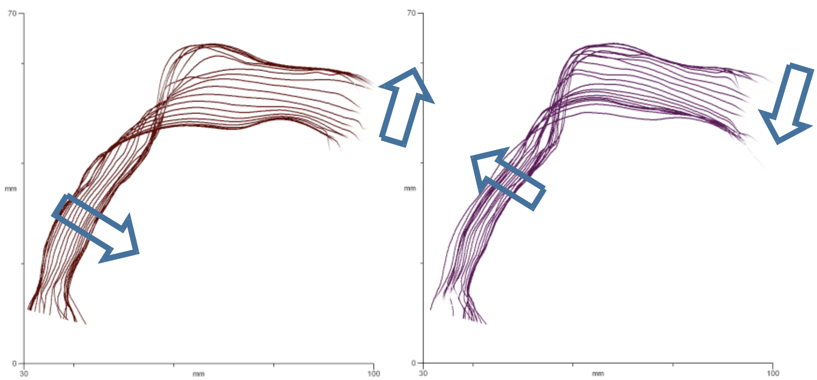


Figure 8 – A single token of the dynamic movement into and out of the clear alveolar lateral /l/.

The dark retroflex lateral, like the dark trill, shows a highly stable tongue root in the /a__a/ context (Figure 9) with a retraction and raising of the blade (and perhaps inversion of the tip)[2], followed by a very rapid forward flapping motion. The time spent at the maximum retracted location is brief, around 30 ms. The forward motion of the tongue in the right panel shows analysis artefacts that could be resolved by smoothing multiple tokens: the tongue will actually be moving forwards evenly, but its location is only represented in the raw data along the echo-pulse beams giving rise to the clumping when the tongue surface is nearly parallel to those beams (Wrench & Scobbie 2011).

Generally, the speed of the movement of the tongue into and out of the constrictions has a peak of around 100-150 mm/s (about 50 mm/s faster in the closing gesture than the opening gesture), except for this flap, in which we estimate a closing speed of 200 mm/s and a forward flapping speed of around 400 mm/s. Only the 5th liquid moves as fast in its closing gesture.

[2] It is possible, recall, that there is sublamimal contact here which we cannot represent, though we think on consideration that the contract is surpalaminal.

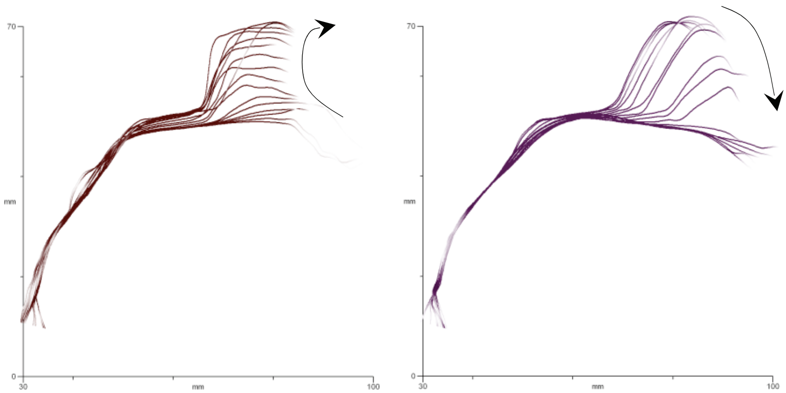


Figure 9 – A single token of the dynamic movement into and out of the darker retroflex lateral /ɭ/. A more detailed path of movement is shown by the thin arrows.

Finally, the 5th liquid has rapid movement in the closing phase, with typically rhotic retraction and raising in a curving path, albeit weakly, and not in a retroflex way. The release of the constriction is, however, rather extraordinary, showing a zig-zig motion that is hard to convey in these diagrams. The movement is, we think, indicative of a change in shape of the blade and tip of the tongue. It may have to do with a transition between a more grooved central and more lateral or slit-like airstream, retraction of the tip, or some other changes in lingual shape. Whatever is the source of this strange movement, we presume the dynamic changes are not accidental, but are associated with the partially rhotic and partially lateral nature of the segment. The opening gesture starts with a downward, slightly retracting opening, quite unlike the tip-down bunched /r/ seen in Lawson et al. (2011). Moreover, at the end of the 5th liquid, in fact in the following /a/, the lowered blade extends forwards again without lowering more, indicating it has been previously retracted into the tongue body. The tip also appears to elongate forwards in /aʐi/ during the /i/. A final possibility is that this apparent motion is mainly due to the filling in of the midsagittal sublingual cavity by the underside of the tip and blade, and that the upper surface of the tongue is hardly moving forward at all.

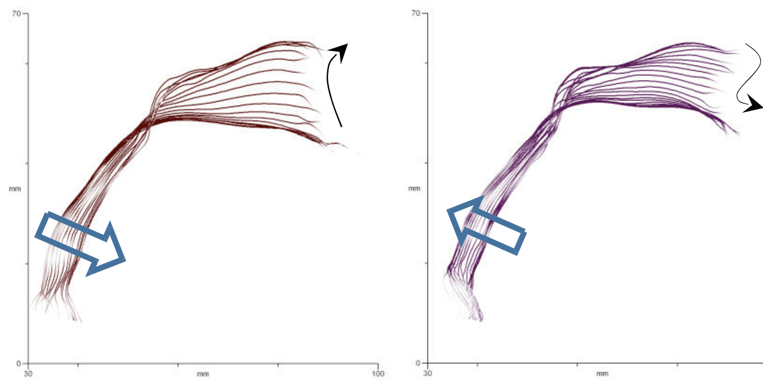


Figure 10 – A single token of the dynamic movement into and out of the clear 5th liquid /ʐ/. The more detailed path of movement is shown by the thin arrows.

Finally, here is an example of the dynamics of an asymmetrical environment for one of the liquids, in this case /r/. Tongue root advancement and palatalization can been seen following the trill, but the root is still very stable before the trill, more so in fact than the root in /aɭi/ where the coarticulatory influence of the /i/ extends more strongly across the whole of the liquid into the preceding vowel.

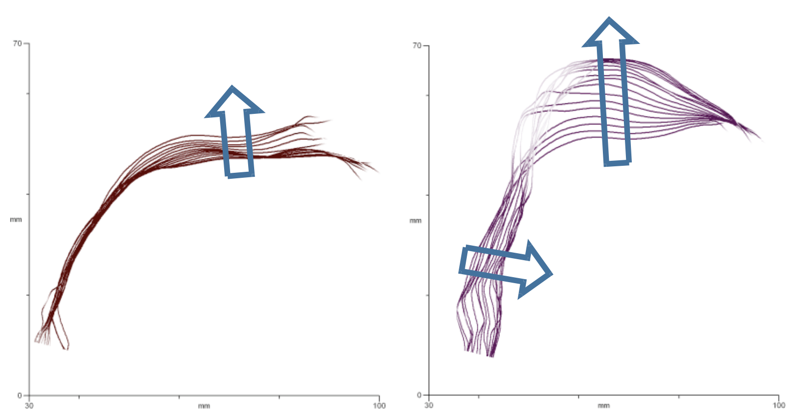


Figure 11 – A single token of the dynamic movement into and out of the darker trill /r/, in /ari/. The right panel shows palatalization (raising) and root advancement in the transition towards the /i/.

4.3 Coarticulation

Some of the liquids have been shown to be clear and others dark, acoustically (Punnoose 2011) and in articulation (above). Punnoose also examined effect of vowel context on the liquids, and vice versa. With the small amount of data available here, we will chart changes to liquids, looking at the effect of coarticulation of an /i/ vowel compared to the /a__a/ context presented above. We will do this mainly for /aCi/, but also mixing in the small number of /iCa/ materials.

The effects of coarticulation can be seen in Figure 12 and Figure 13 below. For the clear liquids (Figure 12) the tongue root is a little more advanced and there is some independent extra raising of the tongue into the palatal arch, particularly for /l/ and /ɾ/. The 5th liquid may perhaps become more apical and alveolar in conjunction with its slight palatalization (which seems to also include some velarisation).

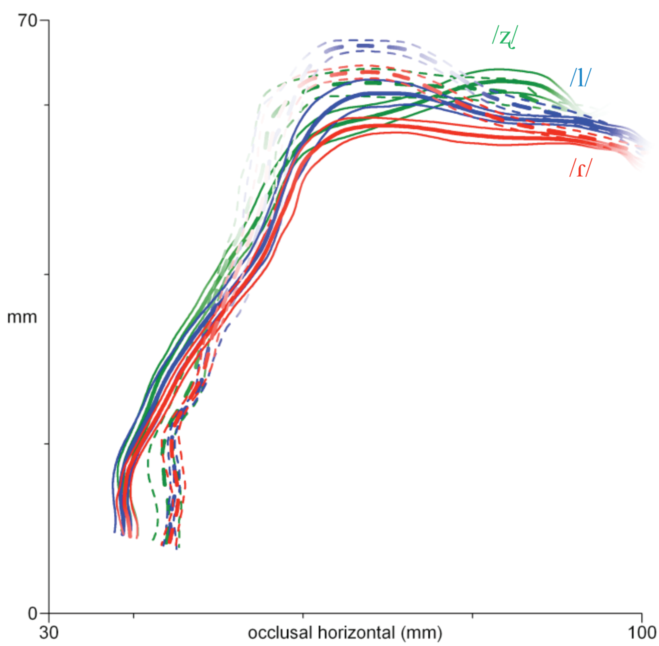


Figure 12 – Mean (thick lines) and standard deviation (thin) of target /ʐ/, tap /ɾ/ and lateral /l/ in /a__a/ context (solid lines) vs. mean targets from mixed /i__a/ and /a__i/ contexts (dashed).

The two dark liquids are shown in Figure 13. Again, the tongue root is a little more advanced and there is a little extra raising for /ɭ/, but there is little change in /r/, which is the most stable of the consonants, as shown above in (Figure 11). The root of the dark consonants, in its advanced state due to the influence of /i/, is still more retracted than the root in the clear consonants.

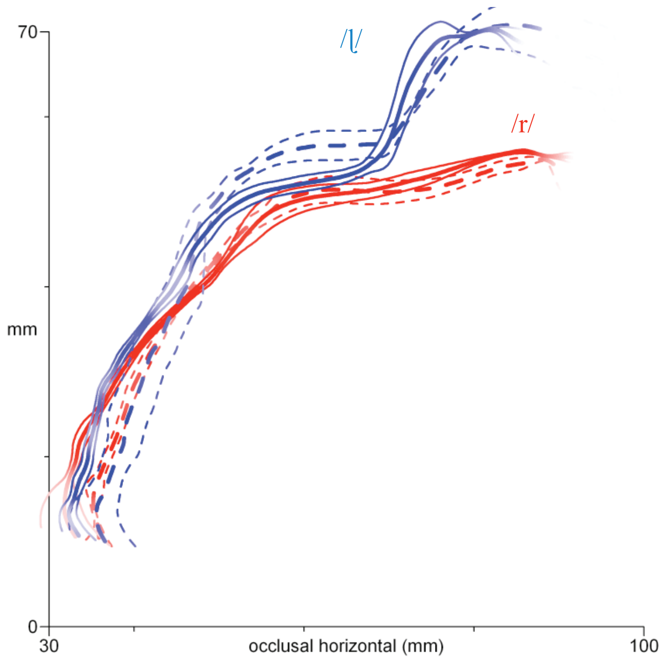


Figure 13 – Mean (thick lines) and standard deviation (thin lines) of target for trill /r/ and retroflex lateral /ɭ/ in /a__a/ context (solid lines) vs. mean from pooled /i__a/ and /a__i/ contexts (dashed).

4.4 Summary

We have presented a qualitative analysis of our small set of articulatory data, which supports the clear/dark distinctions of Punnoose (2011) and Punnoose et al. (2012). We confirm the nature of the distinction between the tap (which is sometimes rather stop-like) and trill (which can undershoot), and between the alveolar and retroflex lateral (which appears flap-like). We also notice unusual activity in the production of the 5th liquid (which otherwise appears to be a post-alveolar approximant cum fricative), the nature of which we have not seen in our previous ultrasound investigations.

Coarticulation to /i/ was found. Impressionistically we noted the appearance of audible and spectrally-visible frication in the liquid when /i/ preceded it, though no difference in tongue shape was apparent (but beware that the sample was very small). The dark trill was particularly resistant to coarticulation, and it may be that both it and the retroflex lateral have a more braced tongue root and dorsum to support their anterior articulations (see below).

5. Previous articulatory research on Tamil and Kannada

5.1 The 5th liquid

McDonough & Johnson (1997) is a single-speaker study which makes a useful point of reference for our work here. They examined the five liquids in the Brahmin dialect of Tamil. This related language also has two rhotics (an alveolar and a retroflex flap); two laterals (an alveolar and a retroflex); and a 5th liquid. The aim of their small-scale study was to investigate the articulatory, acoustic and perceptual characteristics of the five Tamil liquids, in particular the 5th one, in [VCV] contexts. Via electropalatography (EPG) and static palatography, the articulation of the Tamil 5th liquid was shown to involve tongue contact on the hard palate, as is typical for retroflex sounds. However, unlike /ɽ/ there was no evidence of any forward motion during the consonant closure, and unlike /ɭ/ there was no opening at the rear lateral edge of the palate in the EPG data.

A difference was also found between /ɽ/ and /ɭ/ vs. /ʐ/, in that the linguogram and EPG data showed a mid-sagittal gap in contact between the tongue and the palate, suggesting a dip behind the main constriction of /ʐ/. Taken with their acoustic results, McDonough & Johnson describe this segment as being “an apical retroflex central approximant with static articulation, no laterality and only incidental frication” (McDonough & Johnson 1997: 22).

In our Malayalam speaker, the 5th liquid is certainly not static in its active articulator, though we cannot tell how the contact patterns change, nor whether there is any laterality. There appears, for our speaker, to be more friction, and the constriction appears laminal.

Narayanan et al. (1999) also studied sustained productions of each of the Tamil liquids in a word-final /paC/ context, though the methodologies were rather different. The first author produced each liquid, and was recorded using static palatography, magnetic resonance imaging (MRI), and electromagnetic magnetometry (EMMA). They found the 5th liquid (in their transcription system it was /ɻ/) involved an anterior tongue body articulation with the narrowest constriction in the palatal region, though the exact location varied in an inconsistent way. The 5th liquid's back cavity was larger than the other liquids in Tamil (due to root advancement) and was 'depressed' around its retroflex constriction, as had also found by McDonough & Johnson (1997). However, unlike McDonough & Johnson's findings, both the 5th liquid and the retroflex lateral had a dynamic circular kinematic character, which is more similar to what was seen here for the 5th liquid and retroflex lateral in our Malayalam speaker, whose movement was, in addition, more complex than a simple circular movement.

Taking articulatory and acoustic data together, both McDonough & Johnson (1997) and Narayanan et al. (1999) suggest that the 5th liquid in Tamil is a central retroflex approximant, therefore a third rhotic. However, their description of the type of retroflex articulation (static vs. back-to-front) reveals contradictory findings with each other (and with our observations). Furthermore, their findings reveal perceptual and spectral similarity between this sound and the retroflex lateral, which might explain some of the controversy surrounding the identity of the 5th liquid, although acoustic evidence was presented to argue for a classification of the Tamil 5th liquid as a rhotic. We have only discussed the acoustics of the speaker here briefly, but Punnoose (2011) and Punnose et al. (2012) explore Malayalam acoustic patterns in detail, looking at the first four formants of the liquids, along with their phonotactics, and conclude that both resonance and primary liquid manner may be equally relevant in understanding the system and placing the 5th liquid in it, a conclusion which suggests that further comparative research on these related languages would be highly desirable, not least because it may be unlikely that we find the same pattern in each.

5.2 Retroflexion and tongue-root stability

Such broader cross-linguistic work is under way. Recently, Kochetov et al. (2012) looked at (geminate) obstruents in Kannada and found that the retroflex stop in an /a__a/ context had a fronted tongue root compared to other geminate obstruents. It is not clear yet whether this is characteristic of any other retroflexes in Kannada, or how Kannada liquids behave, just as it is not clear what happens in Malayalam retroflex obstruents. From Kochetov et al.'s figures, we estimate that the root moves forward in Kannada from a neutral or /a/-like position ~300 ms before the centre of the voiceless retroflex stop by about 5 mm-10 mm. Contrast this with the highly stable (retracted) root in the Malayalam retroflex lateral above (Figure 9) in the same vowel context. In Malayalam there is root movement in a *front* vowel context – indeed the extent of movement in the retroflex lateral flap in an /a__i/ context seems comparable to the Kannada /a__a/ context, both from /a/ forwards to /ɭ/ (the shape charted in Figure 13) and then again to /i/ (Figure 14). The location of the forward-moving constriction has, however, the same anterior place of articulation as it does in /aɭa/. Kochetov notes that earlier articulatory research on Tamil (including Narayanan et al. 1999) had also found that the pharyngeal cavity was wider in retroflexes than in dentals (and the neutral position).

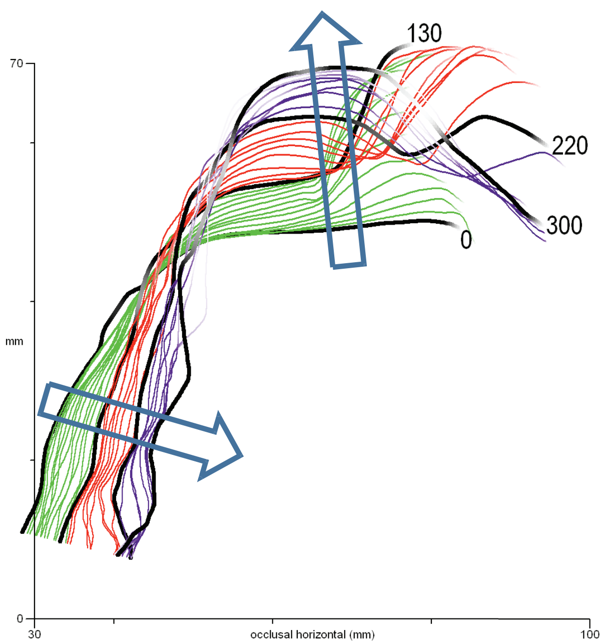


Figure 14 – /aɭi/ from the start of the word (0 ms) with 10 ms tracings and thicker lines representing the shape at the time of the most retracted blade (130 ms), at the time of an acoustic flap event at the transition between /ɭ/ and /i/ (220 ms) and when the target for /i/ was reached during the 2nd vowel (300 ms).

Since the root in Malayalam liquids seems to have a different target in clear vs. dark resonant liquids and, to a lesser extent, varies due to coarticulation with an adjacent vowel, we might expect Kannada and Tamil liquids to be similar, in a way that would be predictable from their acoustic resonance.

6. Conclusions

This was a single-speaker study, with the modest aim of providing preliminary results which are likely mainly to raise questions and hypotheses for future research; but the results here do seem to fit well with the findings of Punnoose (2011), at least for the liquids in an intervocalic /a__a/ context, as well as with those of Narayannan et al. (1999) for Tamil in terms of showing a rather rhotic lingual articulation for the 5th liquid. The high speed ultrasound data has also revealed better than other articulatory techniques some of the coarticulatory and dynamic complexity of these sounds. Of course, we need to look at other speakers, materials, and styles, to get an idea of how articulation can vary, before we can conclude what the *key* elements of the system are. For example, for a proper phonological analysis we need to know if certain speaker groups rely on the clear/dark resonance difference as much as, or more than, differences in manner or primary place, and in what sorts of tasks and contexts. Moreover, we would need to check whether the presence of the ultrasound headset and probe, or just the recording set-up, might have affected any of the articulations here – this speaker seemed to have quite a lot of frication and to produce his taps more as short stops, and the retroflex lateral as a flap rather than as a plain approximant.

One general question for future work relates to the extremely stable nature of the root in the trill and retroflex flap in the /a/ context (and their reduced but still evident stability elsewhere, i.e. in /aCi/ and /iCa/ contexts). Is this intrinsic stabilization of the back of the tongue in liquids of this type indicative of a very high coarticulatory resistance (Recasens & Pallarés 1999; Zharkova & Hewlett 2009), perhaps because bracing is required to facilitate trilling or other complex anterior articulation (Narayanan et al. 1999). If Recasens & Pallarés (1999) found high stability for the Catalan trill, using acoustic and electropalatography (EPG) data, then our results might confirm their comment that *unlike* the tap (our emphasis), the Catalan trill "involves a high degree of tongue body constraint" (ibid:163). On the other hand, the stability or not in this /a__a/ context may be a reflection of the different clear/dark resonances of these liquids in Malayalam.

As a reviewer pointed out to us, these need not be antagonistic or independent goals. It may be the case that the characteristic dark resonances are the acoustic signature of a retracted and stabilized tongue body, a point argued previously on the basis of data on trills in Russian (Kavitskaya et al. 2009; Proctor 2011) and Spanish (Proctor 2011). The coarticulatory pressure from a nearby vowel, /a/, the language-specific characteristic of darkness, and the tendency for a stabilized root in the trill and retroflex flap may all come together to create the immobility seen in Figures 6 & 9. More work needs to be done on the effect of other vowel contexts on the Malayalam liquids to work out the relative importance of these factors.

From the existing ultrasound research on 4 speakers of Spanish (Proctor 2011), we can surmise that the trill and tap appear *alike* in showing little root movement in the /a__a/ context, compared to /d/ and /l/, but it is hard to be sure from Proctor's data's narrower field of view, in which less of the root is imaged. As noted above, our Malayalam data shows a clear dynamic difference between the dark trill and clear tap in this vowel context. Proctor focuses on the 'dorsum' or 'body' in the liquids, noting "during the production of the trill, in contrast to the obstruent, the tongue body moves up and forward – away from the articulatory target of the context vowel – which suggests that this movement is intrinsic [to /r/]" (ibid:457). He also states that dorsal advancement is seen in the tap and lateral. In an /e__e/ context, however, the lateral and tap are stable, while the dorsum retracts as the tongue moves from the preceding vowel into the trill. The location of this intrinsic dorsal target varies from liquid to liquid in Spanish: the lateral has an advanced dorsum, the trill a retracted one, and the tap is intermediate. We saw above (Figure 11) that the tongue root and dorsum in Malayalam also move, in the release of the trill towards a following front vowel. The targets for the liquids, as in Spanish, show coarticulation from the flanking vowel (Figures 12, 13). The root is more advanced next to /i/ in all five liquids, but while the dorsum is raised in the three clear ones and in the dark retroflex lateral tap, it is not raised in the trill. The trill is therefore the most stable liquid, and in fact this is comparable to Spanish when considering *just* /e/ and /a/ contexts: coarticulation in the trill is only evident once /u/ is taken into account, which we cannot do here. Proctor's quantification of coarticulation suggests all three liquids' dorsal constrictions vary to similar degrees, something else we cannot examine in our own limited data.

Russian is interestingly different to Malayalam since it has contrastive clear / dark resonances. Briefly, Proctor's (2011) study of 4 speakers found the dark (non-palatalised) trill and lateral were more dorsally stable across different vowel contexts than a non-palatalised /d/, indicating greater stability in that area. Clear liquids also showed more dorsal stability than the comparable clear obstruent. In sum: the clear liquids (and obstruent) had a palatal ('anterior dorsal') target; the non-palatalised /l/ had a uvular-pharyngeal target; and the non-palatalised trill was rather intermediate with a backish target.

In general, if we could get more articulatory data to augment the mid-sagittal view, it would be particularly useful for understanding the laterals and the

5th liquid. In the AAA multi-channel system it would be easy to add synchronized lip video (60 fps) and EPG (200 fps), which can be captured simultaneously with hs-UTI. EPG gives excellent spatio-temporal information on anterior tongue-palate contact for taps and trills, as shown by Recasens & Pallarés (1999), and centre-only contact to indicate the presence of laterals (cf. Scobbie & Pouplier 2010 for English), and both these studies also show how EPG can be used to detect secondary articulation.

Additionally, it would be very useful to get some coronal section data from ultrasound, in an attempt to understand how the tongue surface of the tip and blade deforms, stretches and moves to enable lateral airstream(s) and hence alter the resonance characteristics of the complex oral cavity tube(s). However, as with the data here, the sublingual cavity would prevent us gaining a complete view of the tongue tip, and coronal scans cannot be made simultaneously with the mid-sagittal scans with current equipment. A high-speed MRI system might also be able to capture the relevant articulation.

We think such extra information would be particularly useful for understanding Malayalam's 5th liquid. The tongue surface data we have seen, augmented by our visual inspection of tongue-internal features, suggests that there are volumetric changes in the tongue blade that the mid-sagittal curves simply do not capture well. The tip seems to extend forward during the following vowel, suggesting it has been retracted during the liquid. While a flesh-point tracking technique like EMA (electromagnetic articulography) would be very useful in showing how the blade and tip upper surface might be extending, it would be harder to get dynamic data on how the tip might be thinning or lowering laterally, without, that is, the challenge of fixing a coil to the sensitive sublingual surface.

Finally, it may be the case that a categorical analysis of the 5th liquid as either a rhotic or lateral liquid is not desirable, phonologically. It is, after all, an ambiguous segment. Its phonetic characteristics would not seem to be predicted by a simple formal phonological classification of this segment as being 'rhotic', or not. We do of course need more articulatory data. If this 5th liquid does indeed have the unusual kinematic properties which are suggested here, i.e. a movement path which we have not observed in typical rhotics or laterals, this would perhaps help to explain its ambiguous status in Malayalam's large liquid set.

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